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Maćkowiak, Piotr

Poznań University of Economics

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THE EXISTENCE OF EQUILIBRIUM IN A SIMPLE EXCHANGE MODEL

PIOTR MAĆKOWIAK

ABSTRACT. This paper gives a new proof of the existence of equilibrium in a simple model of an exchange economy. We first formulate and prove a simple combinatorial lemma and then we use it to prove the existence of equilibrium. The combinatorial lemma allows us to derive an algorithm for the computation of equilibria. Though the existence theorem is formulated for functions defined on open simplices it is equivalent to the Brouwer fixed point theorem.

1. INTRODUCTION

Consider an economy with n goods populated with a finite number m of consumers whose preferences \succeq_i , defined on \mathbb{R}_+^n , are continuous, strictly monotone and strictly convex.¹ Suppose also that each consumer possesses a stock $\omega^i \in \mathbb{R}_+^n$ of goods and that the (total) supply $\omega = \omega^1 + \dots + \omega^m$ is positive, $\omega > 0$. Suppose that at each positive price vector $p = (p_1, \dots, p_n)$ each consumer i wants to maximize his/her preferences among affordable bundles of goods, i.e. he/she plans to buy a bundle of goods $x^i(p) \in \mathbb{R}_+^n$ such that its value $px^i(p)$ is not greater than the value $p\omega^i$ of the disposable stock ω^i and $x^i(p)$ is the best among affordable bundles: $px \leq p\omega^i$, $x \in \mathbb{R}_+^n$, $x \neq x^i(p)$ implies $x^i(p) \succeq_i x$ and it is not true that $x \succeq_i x^i(p)$. The monotonicity of preferences implies that $px^i(p) = p\omega^i$. Hence, at the given

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¹Precise definitions can be found in [2] or [1, Chapter 1]. The presented description of exchange economies goes along the lines of [1, pp. 29-31] and is rather standard.

prices p , it holds $px(p) = p\omega$, where $x(p) = x^1(p) + \dots + x^n(p)$ is the (total) demand for goods at prices p . Plans of all consumers can come into effect only if $x(p) = \omega$ - again by the monotonicity assumption on preferences. Does there exist an equilibrium price vector, i.e. a positive price vector p such that $x(p) = \omega$? It is well known that the answer to that question is positive - see [2] for a survey of the basic existence results. It is obvious that p is an equilibrium price vector if and only if the difference $z(p) := x(p) - \omega$ vanishes. If we allow p to vary over the positive orthant of \mathbb{R}^n we obtain the function z - the excess demand function of the economy. One can show that z is homogeneous of degree zero, continuous on the set of positive prices, it satisfies Walras' law and a boundary condition, and it is bounded from below [1, Theorem 1.4.4]. One can also show that if a function f defined on the positive orthant of \mathbb{R}^n possesses the properties listed in the previous sentence, then there exists an economy whose excess demand function z is different from f only on a neighborhood of the boundary of \mathbb{R}_+^n in \mathbb{R}^n and the set of equilibrium prices for z coincides with the set of zeros of f [6]. In this work we are going to use the excess demand approach to prove the existence of equilibrium [2, Section 3]: we just impose conditions a function should possess to be the excess demand function of an economy and then we prove that there exists an equilibrium price vector.² The novelty of our approach is that we are proving the existence of equilibrium (see Theorem in Section 4) in a new and constructive way.³ It is important to emphasize that we do not rely on the Sperner lemma [10, p. 19] to prove the result. Instead of that we introduce a combinatorial lemma (Lemma 1) formulated for a special triangulation of a closed simplex only. The particular triangulation decreases generality of the lemma but is computationally advantageous [10, p. 65].⁴

In the next section we introduce notation. Section 3 presents necessary notions from combinatorial topology and ends with the combinatorial lemma (Lemma 1). In Section 4 we define the notions of excess demand function and equilibrium, and then we derive some properties of excess demand functions. Finally, we prove the existence theorem. Section 5 contains an algorithm for computation of equilibria. In Section 6 we clarify some differences between the boundary condition we use (see Definition 1.(3)) and the standard boundary condition met in the literature. We also present a connection between fixed points of continuous functions

²Homogeneity of degree zero is among these conditions: we can restrict our considerations to excess demand functions defined on the open standard simplex and not on the whole positive orthant of \mathbb{R}^n - see Definition 1 in Section 4.

³*Constructive* in the sense that it allows to derive a (simplicial) algorithm for computation of an approximate equilibrium.

⁴We find [10] by Z. Yang as a comprehensive source of information on computation of equilibria and fixed points. Since the primary goal of this paper is to derive the existence of equilibria in a novel way without referring to Brouwer's fixed point theorem and not to construct algorithm for computation of equilibria, the algorithm presented below should be treated as a by-product which is important, as we believe, but whose properties should be examined in the future.

and equilibria (zeros) of excess demand functions. At the end of Section 6 we pose a few open questions.

2. NOTATION

Let \mathbb{N} denote the set of positive integers and for any $n \in \mathbb{N}$ let \mathbb{R}^n denote the n -dimensional Euclidean space, and $[n] := \{1, \dots, n\}$, $[0] := \emptyset$. Moreover, e^i is the i -th unit vector of the standard basis of \mathbb{R}^n , where $i \in [n]$. In what follows, for $n \in \mathbb{N}$ the set $\Delta^n := \{x \in \mathbb{R}_+^n : \sum_{i=1}^n x_i = 1\}$, where \mathbb{R}_+ is the set of non-negative real numbers, is the standard $(n-1)$ -dimensional (closed) simplex and $\text{int}\Delta^n := \{x \in \Delta^n : x_i > 0, i \in [n]\}$ is its (relative) interior. For a set $X \subset \mathbb{R}^n$, $\partial(X)$ denotes its boundary (or relative boundary of the closure of X if X is convex). For vectors $x, y \in \mathbb{R}^n$ their scalar product is $xy = \sum_{i=1}^n x_i y_i$. The Euclidean norm of $x \in \mathbb{R}^n$ is denoted by $|x|$. For any set A , $\#A$ denotes its cardinality.

3. DEFINITIONS, FACTS AND A COMBINATORIAL LEMMA

We need some more or less standard definitions and facts from combinatorial topology - they can be found in [10] and [7]. Let us fix $n \in \mathbb{N}$.

- Let $v^j \in \mathbb{R}^n$, $j \in [k]$, $k \leq n+1$, be affinely independent. The set σ defined as $\sigma := \{x \in \mathbb{R}^n : x = \sum_{j=1}^k \alpha_j v^j, \alpha \in \Delta^k\}$ is called a $(k-1)$ -simplex with vertices v^j , $j \in [k]$. We write it briefly as $\sigma = \langle v^j : j \in [k] \rangle$ or $\sigma = \langle v^1, \dots, v^k \rangle$. If we know that σ is a $(k-1)$ -simplex, then the set of its vertices is denoted by $V(\sigma)$. If $p \in \sigma$, then the vector $\alpha^p := (\alpha_1^p, \dots, \alpha_k^p) \in \Delta^k$ is called the vector of the barycentric coordinates of p in σ , if $p = \sum_{j=1}^k \alpha_j^p v^j$. For each $p \in \sigma$ its barycentric coordinates α^p in the simplex σ are uniquely determined.
- If σ is a $(k-1)$ -simplex, then $\langle A \rangle$, where $\emptyset \neq A \subset V(\sigma)$, is called a $(\#A-1)$ -face of σ .
- A collection $\{\sigma_j : j \in [J]\}$, $J \in \mathbb{N}$, of nonempty subsets of a $(k-1)$ -simplex $S \subset \mathbb{R}^n$, $0 < k \leq n+1$, is called a triangulation of S if it meets the following conditions:
 - (1) σ_j is a $(k-1)$ -simplex, $j \in [J]$,
 - (2) if $\sigma_j \cap \sigma_{j'} \neq \emptyset$ for $j, j' \in [J]$, then $\sigma_j \cap \sigma_{j'}$ is a common face of σ_j and $\sigma_{j'}$,
 - (3) $S = \bigcup_{j \in [J]} \sigma_j$.
- Two different $(k-1)$ -simplices $\sigma_j, \sigma_{j'}$, $j, j' \in [J]$, $j \neq j'$, in a triangulation of a $(k-1)$ -simplex S are adjacent if $\langle V(\sigma) \cap V(\sigma') \rangle$ is a $(k-2)$ -face for both of them. Each $(k-2)$ -face of a simplex σ_j , $j \in [J]$, is a $(k-2)$ -face for exactly two different simplices in the triangulation, provided the $(k-2)$ -face is not contained in $\partial(S)$.

- The K -triangulation of an $(n-1)$ -simplex $S = \langle v^1, \dots, v^n \rangle \subset \mathbb{R}^n$ with grid size m^{-1} , where m is a positive integer,⁵ is the collection of all $(n-1)$ -simplices σ of the form $\sigma = \langle p^1, p^2, \dots, p^n \rangle$, where vertices $p^1, p^2, \dots, p^n \in S$ satisfy the following conditions:
 - (1) each barycentric coordinate $\alpha_i^{p^1}$, $i \in [n]$, of p^1 in S is a non-negative multiple of m^{-1} ,
 - (2) $\alpha^{p^{j+1}} = \alpha^{p^j} + m^{-1}(e^{\pi_j} - e^{\pi_{j+1}})$, where $\pi = (\pi_1, \dots, \pi_{n-1})$ is a permutation of $[n-1]$, α^{p^l} is the vector of the barycentric coordinates of p^l , $l \in \{j, j+1\}$, $j \in [n-1]$.

The K -triangulation of S with grid size m^{-1} is denoted by $K(S, m)$ and the set of all vertices of simplices in $K(S, m)$ is denoted by $V(S, m)$. Obviously, $V(S, m) = \bigcup_{\sigma \in K(S, m)} V(\sigma) = \{\alpha_1 v^1 + \dots + \alpha_n v^n : \alpha \in \Delta^n, \alpha_i \in \{0, 1/m, \dots, 1 - 1/m, 1\}\}$. For any $\varepsilon > 0$ and for a sufficiently large m each simplex in $K(S, m)$ has the diameter not greater than ε . Moreover, there exists exactly one simplex in $K(S, m)$ such that v^n is its vertex.⁶

A basic tool used in the proof of our main result is the following

Lemma 1. *Let $S := \langle v^1, \dots, v^n \rangle \subset \mathbb{R}^n$ be an $(n-1)$ -simplex and $l : V(S, m) \rightarrow \{0, 1, \dots, n\}$, $m \geq 2$, be a function satisfying for all $p \in V(S, m)$ the following conditions:*

- (1) $\alpha_i^p = 0 \Rightarrow l(p) \neq i$, $i \in [n-1]$,
- (2) $l(p) = 0$ if $\alpha_n^p = 0$,
- (3) $l(p) = n$ if $\alpha_n^p = 1$,
- (4) $l(p) \in [n-1]$ if $0 < \alpha_n^p < 1$.

Then there exists a unique finite sequence of simplices $\sigma_1, \dots, \sigma_J \in K(S, m)$, $J \in \mathbb{N}$, such that σ_j and σ_{j+1} are adjacent for $j \in [J-1]$, $n \in l(\sigma_1)$, $0 \in l(\sigma_J)$, $[n-1] \subset l(\sigma_j)$, $j \in [J]$, and $\sigma_{j+1} \notin \{\sigma_1, \dots, \sigma_j\}$, $j \in [J-1]$.⁷

Proof. Let σ_1 denote the unique simplex in $K(S, m)$ whose vertex is $p^n := v^n$. Vectors of the barycentric coordinates of vertices of σ_1 (other than p^n) are of the form

$$\alpha^{p^j} = (0, \dots, 0, \underbrace{m^{-1}}_{j\text{-th coordinate}}, 0, \dots, 0, 1 - m^{-1}), j \in [n-1].$$

Since $\alpha_i^{p^j} = 0$ implies $l(p^j) \neq i$, then $l(p^j) = j$, $j \in [n]$ and therefore $[n-1] \subset l(\sigma_1)$. Moreover, since for all $v \in V(S, m)$ $\alpha_i^v = 0$ implies $l(v) \neq i$, then $l(\sigma') = [n-1]$ entails

⁵Our K -triangulation is called the $K_2(m)$ -triangulation in [10, p. 64].

⁶We could not have found a reference for this statement but its proof is elementary.

⁷For simplicity: if we know that σ is a simplex we write $l(\sigma)$ instead of - formally correct way - $l(V(\sigma))$. Notice, that the codomain of the function l could be easily changed to $[n-1]$ in place of $[n] \cup \{0\}$, but we do not do that to discern the 'top' of a simplex from its 'bottom' - see Figure 1.

σ' is not contained in $\partial(S)$, where σ' is an $(n - 2)$ -face of some $\sigma \in K(S, m)$. Whence, no $(n - 2)$ -face of $\sigma \in K(S, m)$ on whose vertices function l assumes all values in $[n - 1]$ is contained in the boundary of S . Further, there exists exactly one $\sigma_2 \in K(S, m) \setminus \{\sigma_1\}$ which is adjacent to σ_1 . Obviously, $l(\sigma_2) = [n - 1]$. Let p_{n+1} be the only element of $V(\sigma_2) \setminus V(\sigma_1)$. Since $l(\{p^1, \dots, p^{n-1}\}) = [n - 1]$ and $l(p^{n+1}) \in [n - 1]$, there exists exactly one vertex p^{i_1} among p^1, \dots, p^{n-1} such that $l(p^{i_1}) = l(p^{n+1})$ and function l attains all values in $[n - 1]$ on the $(n - 2)$ -face $\langle V(\sigma^2) \setminus \{p^{i_1}\} \rangle$. So we can find a simplex $\sigma_3 \in K(S, m) \setminus \{\sigma_1, \sigma_2\}$ adjacent to σ_2 with $[n - 1] \subset l(\sigma_3)$, and if $0 \in l(\sigma_3)$ - the process is complete, if not - proceeding as earlier we can find a simplex $\sigma_4 \in K(S, m) \setminus \{\sigma_1, \sigma_2, \sigma_3\}$ and so on.⁸ Suppose we have constructed the sequence $\sigma_1, \dots, \sigma_J$. If $0 \in l(\sigma_J)$, then the sequence satisfies the claim. Suppose that $0 \notin l(\sigma_J)$. Since each $(n - 2)$ -face which is not contained in $\partial(S)$ is shared by exactly two simplices of $K(S, m)$, there exists precisely one simplex σ' in $K(S, m) \setminus \{\sigma_1, \dots, \sigma_J\}$ such that σ_J and σ' share the $(n - 2)$ -face $\sigma' \cap \sigma_J$ with $l(\sigma' \cap \sigma_J) = [n - 1]$ - this ensures that $\sigma_{J+1} = \sigma'$ and that no simplex of $K(S, m)$ appears twice (or more) in the sequence $\sigma_1, \dots, \sigma_{J+1}$, where $0 \notin l(\sigma_J)$. Thus, in view of the finiteness of $K(S, m)$ and since $l(\sigma') = [n - 1]$ implies σ' is not contained in $\partial(S)$, we conclude that there exists J such that $0 \in l(\sigma_J)$, otherwise we could construct an infinite sequence of simplices built of finitely many different elements of $K(S, m)$, which would imply that a simplex appears more than once in the sequence - an absurd. The choice of σ_{j+1} guarantees that $\sigma_{j+1} \notin \{\sigma_1, \dots, \sigma_j\}$, $j \in [J - 1]$. Uniqueness of the constructed sequence comes from the preceding sentence, uniqueness of the simplex containing v^n , and the fact that each $(n - 2)$ -face in the (relative) interior of S is shared by exactly two simplices of the triangulation. \square

4. THE EXISTENCE OF EQUILIBRIUM

Definition 1. *Let us fix $n \in \mathbb{N}$. We say that a function $z : \text{int}\Delta^n \rightarrow \mathbb{R}^n$, $z(p) = (z_1(p), \dots, z_n(p))$, is an excess demand function, if it satisfies the following conditions:*

- (1) z is continuous on $\text{int}\Delta^n$,
- (2) Walras' Law holds, that is, $pz(p) = 0$ for $p \in \text{int}\Delta^n$,
- (3) the boundary condition holds: if $p^j \in \text{int}\Delta^n$, $j \in \mathbb{N}$, $\lim_{j \rightarrow +\infty} p^j = p \in \partial(\Delta^n)$ and $p_i = 0$ $i \in [n]$, then $\lim_{j \rightarrow +\infty} z_i(p^j) = +\infty$,
- (4) z is bounded from below: $\inf_{p \in \text{int}\Delta^n} z_i(p) > -\infty$, $i \in [n]$.

⁸The method of construction of the sequence is similar to the one used in the proof of the correctness of the Scarf algorithm - see [10, p. 68].

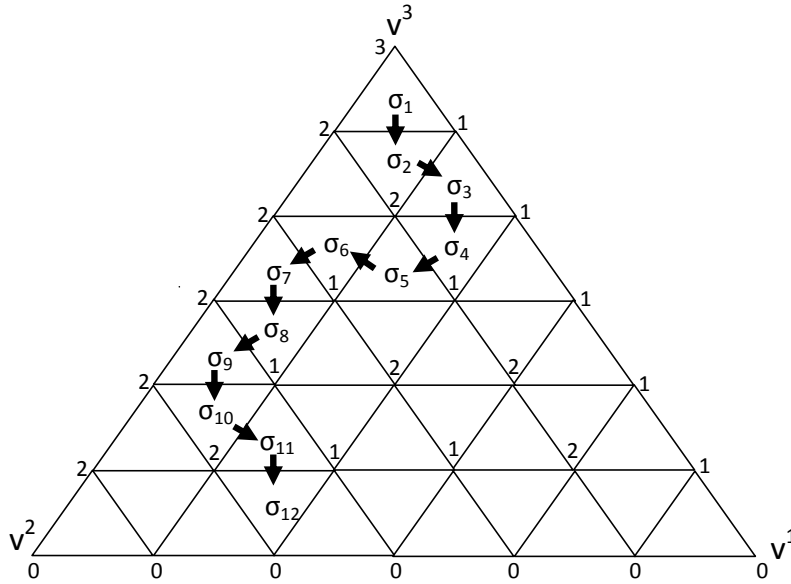


FIGURE 1. The K -triangulation of 2-simplex $S = \langle v^1, v^2, v^3 \rangle$ with grid size 6. The small triangles are members of the triangulation $K(S, 6)$. The number at a vertex of a simplex in $K(S, 6)$ is the value of l assigned to the vertex and one sees that l satisfies the assumptions of Lemma 1. The sequence of simplices $\sigma_1, \dots, \sigma_{12}$ meets the requirements described in the proof of Lemma 1.

Definition 2. Let $z : \text{int}\Delta^n \rightarrow \mathbb{R}^n$ be an excess demand function, $n \in \mathbb{N}$. A point $p \in \text{int}\Delta^n$ is called an equilibrium point for z , if $z(p) = 0$.

The main goal of the paper is to give a new proof of the fact that for each excess demand function there exists an equilibrium point. First, we are going to characterize the behavior of z near the (relative) boundary of its domain, which is crucial for the theorem to follow. The intuition for the lemma below is as follows: if the price p_i of a good i is low (in comparison to some other price - prices are standardized; they sum up to 1) then the demand significantly exceeds the supply of that good; if the price p_i is (relatively) high - so all the other prices are low - then the demand for the i -th good is considerably less than its supply.

Lemma 2. *Let $z : \text{int}\Delta^n \rightarrow \mathbb{R}^n$ be an excess demand function. Then there exists $\varepsilon_1 > 0$ such that for $i \in [n]$ and $p \in \text{int}\Delta^n$ we have*

$$(p_i \leq \varepsilon_1 \Rightarrow z_i(p) > 0) \text{ and } (p_i \geq 1 - \varepsilon_1 \Rightarrow z_i(p) < 0).$$

Proof. Suppose that the former implication is not true. Then there exist $i \in [n]$ and a sequence $p^j \in \text{int}\Delta^n$, $j \in \mathbb{N}$: $\lim_{j \rightarrow +\infty} p^j = p$, $p_i = 0$, and $\lim_{j \rightarrow +\infty} z_i(p^j) \leq 0$ - which contradicts the boundary condition. This implies that there exists $\varepsilon_1 > 0$ for which the just considered implication is true and without loss of generality we can assume that $\varepsilon_1 < 1 - \varepsilon_1$. To prove the latter implication observe that $p_i \geq 1 - \varepsilon_1$ implies $p_{i'} \leq \varepsilon_1$, $i \neq i'$, so the first implication guarantees that $z_{i'}(p) > 0$, $i' \neq i$. Now, from Walras' law, we get $0 < \sum_{i' \neq i} p_{i'} z_{i'}(p) = -p_i z_i(p)$, and $z_i(p) < 0$ is satisfied. \square

Lemma 3. *Let z and ε_1 be as in Lemma 2. Let $S_1 := \{p \in \text{int}\Delta^n : p_n \in (0, 1 - \varepsilon_1/2]\}$ and define the function $\tilde{z} : \text{int}\Delta^n \rightarrow \mathbb{R}^{n-1}$ as follows:*

$$\forall p \in \text{int}\Delta^n \quad \tilde{z}(p) := ((1 - p_n)z_i(p) + p_n z_n(p))_{i=1}^{n-1}. \quad (1)$$

Then

- (1) \tilde{z} is continuous,
- (2) \tilde{z} is bounded from below: $\inf_{p \in \text{int}\Delta^n} \tilde{z}_i(p) > -\infty$, $i \in [n-1]$,
- (3) $p_1 \tilde{z}_1(p) + \dots + p_{n-1} \tilde{z}_{n-1}(p) = 0$ for $p \in \text{int}\Delta^n$,
- (4) if $p^j \in S_1$, $j \in \mathbb{N}$, $\lim_{j \rightarrow +\infty} p^j = p \in \partial(\Delta^n)$ and $p_i = 0$, $i \in [n-1]$, then $\lim_{j \rightarrow +\infty} \tilde{z}_i(p^j) = +\infty$,
- (5) $\exists \varepsilon_2 \in (0, \varepsilon_1/2] \forall p \in S_1 \forall i \in [n-1]$:

$$(p_i \leq \varepsilon_2 \Rightarrow \tilde{z}_i(p) > 0) \text{ and } (p_i \geq 1 - \varepsilon_2 \Rightarrow \tilde{z}_i(p) < 0).$$

Proof. The continuity of \tilde{z} is obvious. The boundedness from below of \tilde{z} stems from the fact that z is bounded from below and the weights p_n , $1 - p_n$, are positive and less than 1 for all $p_n \in (0, 1)$. The following equalities show that property (3) is met:

$$\begin{aligned} p_1 \tilde{z}_1(p) + \dots + p_{n-1} \tilde{z}_{n-1}(p) &= \\ &= p_1((1 - p_n)z_1(p) + p_n z_n(p)) + \dots + p_{n-1}((1 - p_n)z_{n-1}(p) + p_n z_n(p)) = \\ &= (1 - p_n)(p_1 z_1(p) + \dots + p_{n-1} z_{n-1}(p)) + \underbrace{(p_1 + \dots + p_{n-1})}_{=1-p_n} p_n z_n(p) = \\ &= (1 - p_n)p z(p) = 0. \end{aligned}$$

If $p^j \in S_1$, $j \in \mathbb{N}$, converges to a point p with $p_i = 0$ for some $i \in [n-1]$ then $(1 - p_n^j)z_i(p^j)$ diverges to $+\infty$ and since the product $p_n^j z_n(p^j)$ is bounded from below it holds: $\lim_{j \rightarrow +\infty} \tilde{z}_i(p^j) =$

$+\infty$. To prove that (5) is true it suffices to observe that for $p \in S_1$ we have $1 - p_n \geq \varepsilon_1/2$ and to proceed as in the proof of Lemma 2 with \tilde{z} in place of z . \square

The formula used to define the function \tilde{z} resembles the linear homotopy between functions

$$((1 - \varepsilon_1/2)z_1(\cdot, \varepsilon_1/2) + (\varepsilon_1/2)z_n(\cdot, \varepsilon_1/2))_{i=1}^{n-1},$$

and

$$((\varepsilon_1/2)z_1(\cdot, 1 - \varepsilon_1/2) + (1 - \varepsilon_1/2)z_n(\cdot, 1 - \varepsilon_1/2))_{i=1}^{n-1};$$

just put t in place of p_n , assume that t changes from $\varepsilon_1/2$ through $1 - \varepsilon_1/2$ and the 'homotopy' is

$$H(p_1, \dots, p_{n-1}, t) := ((1 - t)z_i(\cdot, t) + tz_n(\cdot, t))_{i=1}^{n-1}.$$

But H is not a homotopy since the domain of $H(\cdot, t)$ changes as t changes.

The important thing - which Lemma 3 reveals - is that at each fixed $p_n \in (0, 1)$ the function $\tilde{z}(\cdot, p_n)$ is an excess demand function defined on a simplex of dimension $n - 2$ instead of $n - 1$.⁹

Now suppose that ε_1 and ε_2 satisfy the statement of Lemma 3 and let for $i \in [n]$:

$$\bar{e}^i := \left(\frac{\varepsilon_2}{n-1}, \dots, \frac{\varepsilon_2}{n-1}, \underbrace{1 - \varepsilon_2}_{i\text{-th coordinate}}, \frac{\varepsilon_2}{n-1}, \dots, \frac{\varepsilon_2}{n-1} \right) \in \text{int}\Delta^n. \quad (2)$$

We can assume that the vectors \bar{e}^i , $i \in [n]$, are linearly independent - it suffices to take sufficiently small $\varepsilon_2 > 0$. The set $S_2 := \langle \bar{e}^i : i \in [n] \rangle \subset \text{int}\Delta^n$ is an $(n - 1)$ -simplex with the vertices \bar{e}^i , $i \in [n]$. If $p \in S_2 \cap S_1$, then $p_i \in [\varepsilon_2/(n - 1), 1 - \varepsilon_2]$, $i \in [n - 1]$ and if $\alpha_i^p = 0$ (i.e. $p_i = \varepsilon_2/(n - 1) < \varepsilon_1/2$) then $\tilde{z}_i(p) > 0$; similarly, if $\alpha_i^p = 1$ (i.e. $p_i = 1 - \varepsilon_2 > 1 - \varepsilon_1/2$) then $\tilde{z}_i(p) < 0$. Moreover, if $p \in S_2$ and $p_n \geq 1 - \varepsilon_1$ then $z_n(p) < 0$ and if $p_n \leq \varepsilon_1$ then $z_n(p) > 0$ (see Lemma 2). We are now in a position to prove the main result of the paper.

Theorem. *Let z be as in Lemma 3. For each $\varepsilon > 0$ there exists $p \in \text{int}\Delta^n : z_i(p) \leq \varepsilon$, $i \in [n]$.*

Proof. If $n = 1$ then there is nothing to prove: $\text{int}\Delta^1 = \{1\} \subset \mathbb{R}$ and - by Walras' law - $z(p) = 0$ at $p = 1$. Suppose that $n \geq 2$. Let us fix $\varepsilon > 0$ and define $\varepsilon' := \varepsilon\varepsilon_1$, where ε_1 comes from Lemma 2. Let also S_1 be as in the hypothesis of Lemma 3 and let S_2 be the $(n - 1)$ -simplex with vertices given by (2). By the continuity of the restriction of \tilde{z} to the compact set S_2 there exists $\delta > 0$ such that if $p, p' \in S_2$ and $|p - p'| < \delta$, then $|\tilde{z}(p) - \tilde{z}(p')| < \varepsilon'$. Choose an integer $m \geq 2$ for which all simplices in $K(S_2, m)$

⁹The idea for the definition of \tilde{z} comes from the proof of Theorem 1 in [4] as it comes as a loose suggestion for the proof of our main Theorem below.

have diameter less than $\min\{\delta, \varepsilon_1/4\}$. Let k_1 denote the smallest integer in $[m]$ for which $(1 - \frac{k_1}{m})\frac{\varepsilon_2}{n-1} + (1 - \varepsilon_2)\frac{k_1}{m} \geq 1 - \frac{\varepsilon_1}{2}$ - this ensures that a point $p \in S_2$ whose last barycentric coordinate in S_2 is greater than or equal to k_1/m satisfies $p_n \geq 1 - \varepsilon_1/2$. To justify this statement, observe that $1 - \varepsilon_2 - \frac{\varepsilon_2}{n-1} \geq 1 - 2\varepsilon_2 \geq 1 - \varepsilon_1 > 0$ and $\alpha_n^p \geq k_1/m$ entail

$$\begin{aligned} p_n &= (1 - \alpha_n^p)\frac{\varepsilon_2}{n-1} + (1 - \varepsilon_2)\alpha_n^p = \frac{\varepsilon_2}{n-1} + \left(1 - \varepsilon_2 - \frac{\varepsilon_2}{n-1}\right)\alpha_n^p \geq \\ &\geq \frac{\varepsilon_2}{n-1} + \left(1 - \varepsilon_2 - \frac{\varepsilon_2}{n-1}\right)\frac{k_1}{m} = \left(1 - \frac{k_1}{m}\right)\frac{\varepsilon_2}{n-1} + (1 - \varepsilon_2)\frac{k_1}{m} \geq 1 - \varepsilon_1/2. \end{aligned}$$

The minimality of k_1 assures that for any nonnegative integer $k < k_1$ if $p \in S_2$ and $\alpha_n^p \leq k/m$, then $p_n < 1 - \varepsilon_1/2$ and $p \in S_1$ - the latter implies that the claim of Lemma 3.(5) applies to p . Notice that if $p \in S_2$ and $p_n \geq 1 - \varepsilon_1/2$ then $z_n(p) < 0$ and if $p_n < \varepsilon_1/2$ then $z_n(p) > 0$ (see Lemma 2). Let us define a function l from the set of vertices $V(S_2, m)$ to $[n] \cup \{0\}$ as follows:¹⁰

$$l(p) = \begin{cases} n, & \text{if } \alpha_n^p = 1, \\ 0, & \text{if } \alpha_n^p = 0, \\ \min\{i \in [n-1] : \alpha_i^p > 0\}, & \text{if } 1 > \alpha_n^p \geq k_1/m, \\ \min\{i \in [n-1] : \tilde{z}_i(p) \leq 0\}, & \text{if } k_1/m > \alpha_n^p > 0, \end{cases} \quad (3)$$

where \tilde{z} is defined in (1). For $i \in [n-1]$, if $p \in V(S_2, m)$, $1 > \alpha_n^p \geq k_1/m$, and $\alpha_i^p = 0$ then it is clear that $l(p) \neq i$, since if $l(p) = i$, then we would obtain $\alpha_i^p > 0$. Assume that $p \in V(S_2, m)$ and $0 < \alpha_n^p < k_1/m$. Since $p \in \text{int}\Delta^n$, Lemma 3.(3) ensures that $\tilde{z}_i(p) \leq 0$ for some $i \in [n-1]$ - so, $l(p)$ is well-defined. Moreover, $\alpha_n^p < k_1/m$ implies $\alpha_n^p = k/m$ for some nonnegative integer k such that $k < k_1$ and therefore, due to Lemma 3.(5), it holds that $\tilde{z}_i(p) > 0$ for $\alpha_i^p = 0$ from which we obtain $l(p) \neq i$ whenever $\alpha_i^p = 0$. Therefore, the assumptions of the combinatorial Lemma 1 are satisfied. Hence, there exists a sequence of simplices $\sigma_1, \dots, \sigma_J$ in $K(S_2, m)$ such that σ_j and σ_{j+1} are adjacent and $n \in l(\sigma_1)$, $0 \in l(\sigma_J)$, $[n-1] \subset l(\sigma_j)$, $j \in [J]$. There exists the first simplex in that sequence, call it σ_{j_1} , such that for all $j > j_1$ the last barycentric coordinate of all vertices of σ_j in S_2 are less than k_1/m . Simplices $\sigma_{j_1} \cap \sigma_{j_1+1}$ are adjacent, i.e. they share an $(n-2)$ -face, and in other words, they differ by one vertex only. By the choice of j_1 all vertices $p \in V(\sigma_{j_1+1})$ satisfy $\alpha_n^p < k_1/m$, and there is a vertex $\bar{p} \in V(\sigma_{j_1}) \setminus V(\sigma_{j_1+1})$ such that $\alpha_n^{\bar{p}} \geq k_1/m$. Now, the adjacency of σ_{j_1} and σ_{j_1+1} , the fact that all simplices in $K(S, m)$ have diameters less than $\varepsilon/4$ and the inequality $\bar{p}_n \geq 1 - \varepsilon_1/2$ entail that $p_n \geq 1 - \varepsilon_1$ for $p \in V(\sigma_{j_1+1})$ which implies $z_n(p) < 0$ for $p \in V(\sigma_{j_1+1})$. Reasoning analogously we get for the last simplex, σ_J , that it holds: $z_n(p) > 0$, $p \in V(\sigma_J)$. By the choice of j_1 , all simplices σ_j , $j \geq j_1 + 1$, are contained in $S_1 \cap S_2$. Moreover, their

¹⁰The idea for l is closely related to the notion of the standard integer labeling rule [10, p. 63].

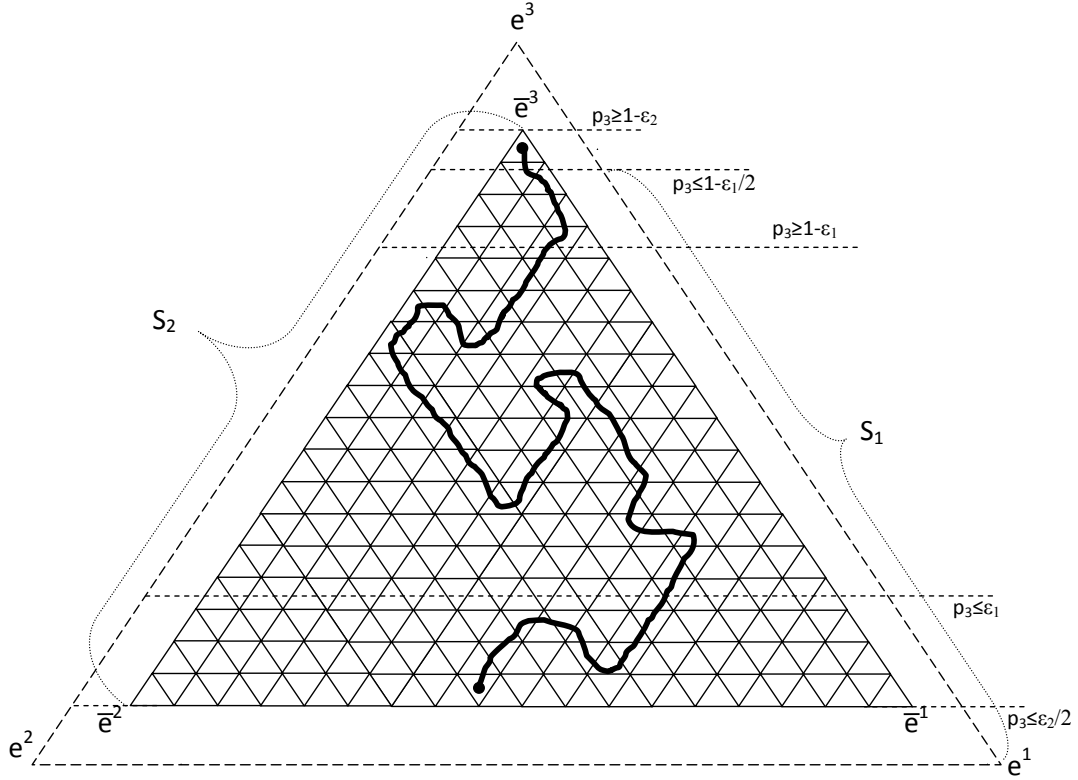


FIGURE 2. This figure explains the idea of the proof of Theorem for $n = 3$. Values of l assigned to the vertices in $V(S_2, m)$ are independent of \tilde{z} if the considered vertex is above or on the line $p_3 \leq 1 - \varepsilon_1/2$ - here the second and third row of the formula (3) are used to define values of l . If a vertex is below the line $p_3 \leq 1 - \varepsilon_1/2$ - but not at the bottom of S_2 - then \tilde{z} is used to compute the value of l . The thick curve presents a hypothetical sequence of simplices $\sigma_1, \dots, \sigma_J$. For vertices of simplices above $(p_3 \geq 1 - \varepsilon_1)$ -line (below $(p_3 \leq \varepsilon_1)$ -line) values of z_n are negative (positive). If σ_j is below $(p_3 \leq 1 - \varepsilon_1/2)$ -line then each coordinate of \tilde{z} admits a non-positive value at a vertex of σ_j . Somewhere between $(p_3 \geq 1 - \varepsilon_1)$ and $(p_3 \leq \varepsilon_1)$ -lines there is a simplex σ_j such that $z_n(p)z_n(p') \leq 0$ for a pair of vertices p, p' of σ_j - that simplex is what we are looking for.

diameters are less than δ so $p, p' \in \sigma_j, j \geq j_1 + 1$, implies $|\tilde{z}_i(p) - \tilde{z}_i(p')| \leq \varepsilon', i \in [n-1]$. Since $\bigcup_{j \geq j_1} \sigma_j$ is (arcwise) connected and $V(\sigma_{j_1}) \cap z_n^{-1}((-\infty, 0)) \neq \emptyset$ and $V(\sigma_J) \cap z_n^{-1}((0, +\infty)) \neq \emptyset$ then - by the continuity of \tilde{z} - there exists a simplex $\sigma_{j_2}, j_2 \geq j_1 + 1 : 0 \in z_n(\sigma_{j_2})$. Let $p \in \sigma_{j_2} : z_n(p) = 0$. So $|p - p'| < \delta, p' \in V(\sigma_{j_2})$. Since for each i there exists a vertex p^i of σ_{j_2} such that $\tilde{z}_i(p^i) \leq 0$ (by the inclusion $[n-1] \subset l(\sigma_{j_2})$), $(1 - p_n)z_i(p) = \tilde{z}_i(p) \leq \tilde{z}_i(p^i) + \varepsilon' \leq \varepsilon', i \in [n-1]$. Further, $z_i(p) \leq \frac{\varepsilon'}{(1 - p_n)} \leq \frac{\varepsilon'}{\varepsilon_1} = \varepsilon, i \in [n-1]$, since $p_n \in [\varepsilon_1, 1 - \varepsilon_1]$, if $z_n(p) = 0$, due to Lemma 2. We have found a point $p \in \text{int}\Delta^n : z_i(p) \leq \varepsilon, i \in [n]$, which ends the proof. \square

Corollary. *Let z be as in the above Theorem. There exists an equilibrium point for z .*

Proof. Let $\varepsilon^q > 0$, $q \in \mathbb{N}$, be a sequence converging to 0. In view of the proof of Theorem, for each $q \in \mathbb{N}$ there exists a point $p^q \in S_2$ such that $z_i(p^q) \leq \varepsilon^q$, $i \in [n]$. The Bolzano-Weierstrass Theorem and compactness of S_2 imply that there exists a convergent subsequence $p^{q'}$ of p^q , such that $\lim_{q' \rightarrow +\infty} p^{q'} = p \in S_2$. From the continuity of z it follows that $z_i(p) \leq 0$, for $i \in [n]$. Since $p \in S_2 \subset \text{int}\Delta^n$, $p_i > 0$, $i \in [n]$. Walras' law ensures that $z(p) = 0$. \square

5. AN ALGORITHM FOR THE COMPUTATION OF EQUILIBRIUM

From the proof of Theorem we can derive the following algorithm for computation of a point $p \in \text{int}\Delta^n$ satisfying $z_i(p) \leq \varepsilon$, $i \in [n]$, where $\varepsilon > 0$ is a given accuracy level. The algorithm below uses the function $l : V(S_2, m) \rightarrow \{0, 1, \dots, n\}$ defined in (3) and we reasonably assume that $n \geq 2$.

Step 0: Determine $\varepsilon_1, \varepsilon_2$ satisfying claim of Lemma 2 and Lemma 3.(5), respectively. Fix accuracy level: $\varepsilon > 0$. Find $\delta > 0$ such that if $p, p' \in S_2$, where S_2 is defined as in the proof of Theorem, and $|p - p'| < \delta$ then $|\tilde{z}(p) - \tilde{z}(p')| < \varepsilon\varepsilon_1$ and let $m \geq 2$ be an integer for which all simplices in $K(S_2, m)$ have diameter less than $\min\{\delta, \varepsilon_1/4\}$. Let σ_1 be as in the proof of Lemma 1 for $S = S_2$, set $\text{FaceVertices} := V(\sigma_1) \setminus \{\bar{e}^n\}$, $\bar{v} := \bar{e}^n$ (see formula (2)) and go to step 1.

Step 1: Determine the only vertex $v \in V(S_2, m)$ such that $v \neq \bar{v}$ and $\langle \text{FaceVertices} \cup \{v\} \rangle \in K(S_2, m)$. Go to step 2.

Step 2: If $\langle \text{FaceVertices} \cup \{v\} \rangle \subset S_1$, where S_1 is defined in Lemma 3, and $z_n(v) > 0$ STOP: v satisfies $z_i(v) \leq \varepsilon$, $i \in [n]$. Otherwise, assign the only element of $l^{-1}(l(v)) \cap \text{FaceVertices}$ as the value of \bar{v} . Set $\text{FaceVertices} := (\text{FaceVertices} \setminus \{\bar{v}\}) \cup \{v\}$ and go to step 1.

Step 0 initializes the necessary parameters for correct course of the algorithm and in fact it is the most difficult part of the algorithm, unless we know some properties of the considered excess demand function (e.g. differentiability, its lower bound or if it is a Lipschitz function on compact subsets of $\text{int}\Delta^n$). It is easy to determine m if we know δ and ε_1 - it suffices to take $m \geq \frac{(n-1)\sqrt{2}}{\min\{\delta, \varepsilon_1/4\}}$, which is a consequence of the definition of the K -triangulation and the fact that the diameter of a simplex equals the maximum distance between its vertices. In Steps 1 and 2 set $\langle \text{FaceVertices} \rangle$ is a face of an element of $K(S_2, m)$ such that $l(\text{FaceVertices}) = [n - 1]$. In Step 2 we check if currently considered simplex $\langle \text{FaceVertices} \cup \{v\} \rangle$, where v is such a vertex in $K(S_2, m)$ that $\langle \text{FaceVertices} \rangle$ is common $(n - 1)$ -face of the currently considered simplex and its direct predecessor $\langle \text{FaceVertices} \cup \{\bar{v}\} \rangle$, is contained in S_1 which

implies that the value of l depends on function \tilde{z} (see Lemma 3 and formula (3)). If it is the case, and in addition $z_n(v) > 0$, then v is what we seek for. If not, we have to find the next adjacent simplex - to this goal we have to decide which vertex should be removed from $FaceVertices$. To achieve this, we find the vertex $\bar{v} \in FaceVertices$ which bears the same value of l as v and we form the new set $FaceVertices$ substituting v in place of \bar{v} and then we repeat the operations. The algorithm succeeds in finding approximate zero in a finite number of iterations due to Lemma 1, the Theorem and its proof. It is worth to emphasize that at a given iteration of the algorithm (Step 1 - Step 2) exactly one new value of l is computed and to proceed on with computations it is sufficient to know only the last simplex - there is no need to remember the earlier stages in the course of the algorithm. Moreover, the values of l need to be computed only at the vertices of the constructed sequence of simplices.

6. FINAL COMMENTS

6.1. The boundary condition. The standard form of the boundary condition imposed on/satisfied by an excess demand functions is:¹¹

$$p^j \in int\Delta^n, j \in \mathbb{N}, \lim_{j \rightarrow +\infty} p^j = p \in \partial(\Delta^n), p_i = 0, \text{ implies } \lim_{j \rightarrow +\infty} \max\{z_i(p^j) : i \in [n]\} = +\infty.$$

The difference is that we assume that if the (relative) price of a good i tends to 0, then the excess demand for the good i goes to $+\infty$. The standard condition claims that if the (relative) price of a good i tends to 0, then the excess demand for some good - not necessarily i - goes to $+\infty$. Our condition is satisfied if there is a consumer with Cobb-Douglas preferences and owns a positive quantity of each good. But even if z is an excess demand function that satisfies the standard boundary condition, we can approximate z (as close as we wish on compact subsets of $int\Delta^n$) with an excess demand function satisfying the version of the boundary condition used in the paper - see the below construction of the function z^h and just put there z in place of g .

6.2. Fixed points of continuous functions defined on the standard simplex. Here we show how to relate a continuous function $f : \Delta^n \rightarrow \Delta^n$ and an excess demand function, for which we can apply our algorithm and we can find approximate fixed points of f . We use a construction by H.Uzawa [9]. Let a continuous function $g : \Delta^n \rightarrow \mathbb{R}^n$ be defined as

$$\forall x \in \Delta^n : g(x) := f(x) - \frac{xf(x)}{xx}x.$$

Since $xg(x) = xf(x) - xf(x) = 0$, then the function g meets Walras' law. Let us fix a number $h > 0$ and define a function $z^h : int\Delta^n \rightarrow \mathbb{R}^n$ as

$$z^h(x) = (z_1^h(x), \dots, z_n^h(x)) := (g_1(x) + h((nx_1)^{-1} - 1), \dots, g_n(x) + h((nx_n)^{-1} - 1)).$$

¹¹See [1, Theorem 1.4.4] or [2, Lemma 4].

One can easily check that z^h is an excess demand function. Now, by the Corollary, we see that for each $h > 0$ there exists a point $x^h \in \text{int}\Delta^n$: $z^h(x^h) = 0$, written equivalently as

$$g_i(x^h) = -h \left(\frac{1}{nx_i^h} - 1 \right), i \in [n].$$

Let $h \rightarrow 0^+$ and $x^h \rightarrow x \in \Delta^n$ (taking a subsequence if necessary). If $x_i > 0$, then $g_i(x) = 0$. If $x_i = 0$ then $\frac{1}{nx_i^h} \rightarrow +\infty$ and $\frac{1}{nx_i^h} - 1 \rightarrow +\infty$, so $-h \left(\frac{1}{nx_i^h} - 1 \right) < 0$, but boundedness of g implies that $-h \left(\frac{1}{nx_i^h} - 1 \right), h > 0$, is bounded. We obtain $g(x) \leq 0$, which ensures that $f(x) = x$ (see [9]). Hence to find an approximate fixed point of f we can apply the algorithm for z^h , h sufficiently small.

The equivalence of the existence of equilibria for excess demand functions defined on the standard closed simplices¹² and Brouwer's theorem was shown in [9]. The proofs of the equivalence for the excess demand functions considered in the current paper can be found in [5] or [8].

6.3. Open questions. Combinatorial Lemma 1 seems to be interesting for its own sake in spite of the fact that it is proved for a particular triangulation. We have seen that it implies the existence of equilibrium for an excess demand function. A slight modification of the proof of Theorem 7 in [5] allows to claim that the existence of equilibrium for an excess demand function is equivalent to the Brouwer fixed point theorem (see also [8]). The famous Sperner lemma which is a combinatorial tool used to prove Brouwer's fixed point theorem (and which is equivalent to it [10, p. 21]) has many implications (e.g. see [3, pp. 101-103]). What are other implications of Lemma 1? Does Lemma 1 generalize to any triangulation of the standard simplex? Is it equivalent to Sperner's lemma? What about the behavior of the algorithm presented in the paper in comparison to the behavior of other computational methods for finding equilibria (e.g. methods presented in [10])? How to modify the algorithm to allow for the computation of (approximate) equilibria of excess demand mappings rather than functions?

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¹²This assumption eliminates both boundary conditions presented above.

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DEPARTMENT OF MATHEMATICAL ECONOMICS, POZNAŃ UNIVERSITY OF ECONOMICS, AL. NIEPODLEGŁOŚCI
10, 61-875 POZNAŃ, POLAND

E-mail address, P. Maćkowiak: p.mackowiak@ue.poznan.pl